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6. AUTHOR(S)
Ronald B. Chase
Alan E. Kehew

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Western Michigan University
Kalamazoo, MI 49008

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13. ABSTRACT *(Maximum 200 words)*
A detailed stratigraphic/geotechnical analysis and three-year monitoring of six hydrostratigraphic scenarios among Lake Michigan shoreline bluffs has been conducted using cross-section balancing and limit equilibrium modeling techniques. Bluffs show no major displacements of glacial materials where perched ground water is absent. Bluffs containing perched water are stable if composed of sand, but unstable where sand and clay are interlayered. Shallow, planar slumps occur where the clay is mostly till, but slumping is more deep-seated and frequent where lacustrine silt/clay layers are present. Displacements are largely by simple shear and by fault-propagation folding. Comparative records of displacements, water table levels, atmospheric temperatures, precipitation, and wave heights shows that: 1) displacements are minimal in the summer and early fall, but accelerate in the late fall and remain rapid through early spring; 2) wave erosion is greatest in the late fall and spring, and nil during the winter; and 3) surface freezing and a rise of perched water levels occur together. Bluff degradation is caused largely of wave action in the fall, freezing of the bluff surface which raises pore pressures and reduces effective stress during the winter, and ground-water release during the early spring thaw.

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SLOPE STABILITY ANALYSIS AND GROUND-WATER HYDROLOGY IN HETEROGENEOUS GLACIAL MATERIAL: ELEMENTS FOR PREDICTION OF BLUFF EROSION

FINAL PROGRESS REPORT

Ronald B. Chase
Alan E. Kehew

February 10, 2000

U.S. ARMY RESEARCH OFFICE

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Western Michigan University

TABLE OF CONTENTS

STATEMENT OF THE PROBLEM STUDIED

The state of knowledge for slope stability in unconsolidated glacial materials is well advanced in the realms of process modeling and limit equilibrium analysis, but lacking in the areas of kinematics and strain partitioning during the movement of real slopes. The Lake Michigan shoreline bluffs (Figure 1) have been the perfect setting for such an empirical study. The variable bluff materials (Monaghan et al., 1986; Chase, 1990), plus the persistence of wave activity, precipitation, ground-water infiltration, and periodic freezing of bluff surfaces provides ideal dynamic conditions for the study of causes and mechanisms of mass movements in a varied energy environment. Continuous monitoring of slope displacements, wave activity, standing ground-water levels, wave heights, precipitation, and atmospheric temperatures shows how strain magnitudes and rates are affected by these factors. Displacement data provide the basis for balanced cross-section constructions that reveal progressively developing folds and shear zones in the failing slopes. In this manner, real data can be used to evaluate the correctness of limit equilibrium computer models generated for these same slopes.

Balanced cross-section modeling techniques, frequently used in the structural analysis of displaced rock bodies (Dahlstrom, 1969, Erslev, 1991, Allmendinger, 1998), are largely ignored by slope engineers in favor of computer reconstructions of shear surfaces. As typically applied in limit equilibrium studies, critical shear surfaces are identified by selecting the lowest factor of safety conditions using input from slope angles, soil layer thicknesses, and soil strength values (such as Bishop, 1955; Morgenstern and Price, 1965; Spencer, 1967; among others)(reviewed extensively in Nash, 1987). Balanced cross-sections automatically generate locations of critical shear surfaces by selecting those most likely to have produced measured surface displacements (Wodward, et al., 1985). Both methods of locating shear surfaces are critical as cross-checks of their predictive capacities for real slope movements. This investigation provides the data set to perform such cross-checks with rigor. In the process, insight into the causes and mechanisms of mass movements in heterogeneous glacial materials has been provided, particularly in slope regions subjected yo ground-water loads.

SUMMARY OF THE RESULTS

The activities conducted during the three-year grant tenure of this project are listed below. The details have been discussed in interim progress reports.

- Geological and engineering characterization of the study site, consisting of 257 measured sections spaced at 60 meter intervals.

- Completion of three ground-water potentiometric surface maps and a subsurface cross-section network for the entire ground-water recharge and discharge area using data from over 400 domestic water wells.

- Detailed geological and engineering descriptions and materials analyses at six monitoring sites.

- Geotechnical characterization of the glacial materials (at the Geotechnical Lab, U.S. Army Corps of Engineers - Waterways Experiment Station, Vicksburg, MS).

- Installation of monitoring systems at six sites (piezometer nests and surface displacement monitoring systems).

- Bi-weekly or tri-weekly (depending on the season) monitoring of ground-water activity and slope displacements at the six sites.

- Daily monitoring of weather and wave activity along the Lake Michigan shoreline.

- Radiocarbon dating of organic horizons to aid in bluff stratigraphic correlations.

- Preliminary calculation and display of slope stabilities at 60 meter intervals using a GIS format.

- Continuous correlation of data related to slope displacements, hydraulic gradients, atmospheric temperature, precipitation, and wave activity.

- Periodic inspection and photo mosaic preparation of the total shoreline bluff to locate and study mass movements distant from the monitoring sites.

- Detailed descriptions of 32 massive slumps located near monitoring sites that developed since May 1, 1996.

- Hindcasting of bluff erosion conditions back to 1938 (the first complete photographic record).

- Production of predictive digital models of bluff failure and factor of safety calculations for a variety of failure models using the UTEXAS3 software.

- Presentation of seven progress reports and eight seminars at scientific meetings and academic functions.

- Submission of one paper to a refereed publication. Five additional manuscripts are in stages of preparation ranging from first draft to near-submission.

The integration of all data from the above investigative activities has led to many insights regarding mechanisms of failure in slopes consisting of heterogeneous glacial materials. Bluff stratigraphy is the key to its relative stability. Bluffs consisting of all sand or all clay are more

stable than bluffs consisting of interlayered sand and clay. This is particularly evident where perched ground-water systems exist. Bluffs composed largely of saturated clay fail along shallow, planar surfaces (Figure 2). By far, the most unstable bluffs occur where the clay is a lacustrine type (varved clay), a fact not surprising in light of the low strength values characteristic of glaciolacustrine deposits (Giraud, et al., 1991). Shear surfaces in new slumps where lacustrine silt/clay forms a significant part of the bluff stratigraphy develop at the toes, then propagate upward through the stratigraphic section as the bluff surfaces collapse downward before they rotate back in a typical slump-like manner (Figure 3). The bluff collapse by "fault propagation folding" is a failure mechanism described for the first time in this study. Interlayered sand-clay bluffs fail along deep-seated fractures that are generally curved, but not classically arcuate (Figure 3). Displacements are minimal during the summer and early fall, but accelerate in late fall and remain rapid through early spring, a cycle that was repeated each of the three years of the study (Figure 4). Wave erosion is greatest in the late fall and spring, and nil during the winter (Figure 5). Surface freezing during the winter (Figure 6) and a rise of perched water levels in the bluff (Figure 7) occur together.

It is very clear that bluff degradation is caused largely by wave action in the fall, freezing of the bluff surface which causes the trapping of ground-water in the soil that is prevented from discharging onto the bluff face, thus increasing pore pressures and reducing effective strength of the soil during the winter, and ground-water release during the early spring thaw when the high pore pressures are maintained by flow. The presence of high ground-water pore pressures are known to reduce slope stability in layered systems (Moriwaki, 1993; Haneberg, 1995), especially during winter-spring time periods (VanGenuchten and Nieuwenhuis, 1990; Haneberg, 1991). Prior to this study, however, only Sterrett and Edil (1982) emphasized the significance of ground-water buildup as a destabilizing influence in the Lake Michigan region. Limit equilibrium computer models are useful to verify the above conclusions by entering measured shear geometries and ground-water conditions into the equations, but such models alone would not have predicted the observed failures. The shear geometries are not those commonly modeled in limit equilibrium studies by slope engineers, and the slope stability is controlled by pore pressure fluctuations to a greater degree than the models would predict. Although computer models assist with the understanding of slope stabilities at specific sites in heterogeneous glacial materials, they need to be carefully verified by "ground truth" before they are accepted as fact.

LIST OF PUBLICATIONS AND TECHNICAL REPORTS

Publications

1996 Chase, R. B., Kehew, A. E., and Montgomery, W. W., Degradation of slopes composed of clay-rich till: Relationships between ground-water activity and accelerated mass movements: *Geological Society of America Abstracts with Programs*, v. 28.

1996 Montgomery, W.W., Chase, R.B., and Kehew, A.E., Stability of the Lake Michigan shore, Allegan County, Michigan - a preliminary hazard map: *Geological society of America Abstracts with Programs*, v. 28.

1997 Chase, R.B., Kehew, A.E., and Montgomery, W.W., Stratigraphic and hydrogeologic controls on mass movements in heterogeneous glacial materials: *Geological Society of America Abstracts with Programs*, v. 29.

1997 Montgomery, W.W., Chase, R.B., Kehew, A.E., and Anderson, G.P., Relationships between lithology, hydraulic head, and shoreline recession on the eastern shore of Lake Michigan: *Geological Society of America Abstracts with Programs*, v. 29.

1998 Chase, R.B., Chase, K.E., Kehew, A.E., and Montgomery, W.W., Determination of slope failure mechanisms in unconsolidated materials using low-cost monitoring and cross-section balancing: *Geological Society of America Abstracts with Programs*, v. 30.

1998 Montgomery, W.W., Chase, R.B., Kehew, A.E., and Torrey, V.H., Factors of safety and relationships to historical bluff recession in Pleistocene deposits on the eastern shore of Lake Michigan: *Geological Society of America Abstracts with Programs*, v. 30.

1999 Chase, R.B., Kehew, A.E., and Montgomery, W.W., Mechanisms and causes of mass movements in heterogeneous glacial materials: examples from the southeastern Lake Michigan shoreline bluffs: *International Association of Great Lakes Research, 42nd Conference Program*, p. A-17 - A-18.

1999 Chase, R.B., Kehew, A.E., and Montgomery, W.W., the destabilizing influences of perched ground water in shoreline bluffs composed of heterogeneous glacial materials: *Geological society of America Abstracts with Programs*, v. 31.

Submitted for Publication

Chase, R.B., Chase, K. E., Kehew, A.E., and Montgomery, W.W., Determining the kinematics of slope movements using low-cost monitoring and cross-section balancing: submitted to *Environmental and Engineering Geoscience*, December 19, 1999.

Papers in Advanced Stages of Preparation

Chase, R.B., Kehew, A.E., and Montgomery, W.W., The causes and mechanisms of mass movements in heterogeneous glacial materials: to be submitted to *Environmental and Engineering Geoscience.*

Chase, R.B., Kehew, A.E., and Montgomery, W.W., Determination of slope kinematics and causes of failure using geometric models and climate data: invited paper in Harmon, R.S., and Doe III, W.W., (eds.) *Landscape Erosion and Evolution Modeling*: New York, Oxford University Press.

Montgomery, W.W., Chase, R.B., Kehew, A.E., and Torrey, V.H., Geotechnical properties of glacial materials from the southeastern coastal bluffs of Lake Michigan and their influence on shoreline recession: *journal yet to be decided.*

Montgomery, W.W., Chase, R.B., Kehew, A.E., and Anderson, G.P., GIS-based shoreline characterization methodology and application to studies of bluff recession along the Lake Michigan coast: *journal yet to be decided.*

Paper in a Preliminary Stage of Preparation

Chase, R.B., The kinematic treatment of slumps as fault propagation fold structures: to be submitted to *Geology*.

REPORTABLE INVENTIONS

None

PARTICIPATING SCIENTIFIC PERSONNEL (AND DEGREES EARNED)

Co-Principal Investigators

Ronald B. Chase
Professor of Geosciences
Western Michigan University

Alan E. Kehew
Professor and Chair of Geosciences
Western Michigan University

Graduate Research Fellows

William W. Montgomery, currently Assistant Professor of Geology, Department of Geosciences/Geography, New Jersey City University, Jersey City, NJ 07305 - **Ph.D., Western Michigan University, April, 1998.** Supported by the grant May 1, 1996 - May 1, 1998. (B.S. - University of Michigan: M.S. - University of Wisconsin-Madison). Dissertation topic: Groundwater Hydraulics and Slope Stability Analysis: Elements for Prediction of Shoreline Recession.

- Received one of two 1996 national awards for outstanding student research by the Hydrogeology Division of the Geological Society of America.

Shannon A. Wong, currently a M.S. candidate in Geosciences at Western Michigan University, anticipated graduation in April, 2000. Supported by the grant May 1, 1998 - May 1, 1999. (B.S. - University of California, Santa Cruz). Thesis topic: Correlation of Till Horizons in the Lake Michigan Shoreline Environment Using Clay Mineralogy.

Undergraduate Assistants

Mark S. Worrall, (1996 - 1998), currently a M.S. candidate in Geosciences at Western Michigan University, anticipated graduation in December, 2000. Thesis topic: Zonation of Failure Potential Along the Shoreline Bluffs of Southeastern Lake Michigan.

Karl E. Chase, (1996 - 1999), currently a sales manager for the Hilton Hotel System.

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Spencer, E., 1967, A method of analysis of the stability of embankments assuming parallel interslice forces: *Geotechnique*, Vol. 17, pp. 11-26.

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VanGenuchten, P.M.B., and Nieuwenhuis, J.D., 1990, On the stability of seasonally sliding soil masses in the French Alps: *Engineering Geology*, Vo. 28, pp. 41-69.

Woodward, N.B., Boyer, S.E., and Suppe, J., 1985, *An Outline of Balanced Cross-Sections*: Knoxville, TN, University of Tennessee Publication, 176 pp.

APPENDIX A

TECHNOLOGY TRANSFER

Presentations of Research

Seminars Presented at the U.S. Army Corps of Engineers - Waterways Experiment Station

March 16, 1996 -	Ronald B. Chase
July 29, 1997 -	William W. Montgomery
October 18, 1999 -	Ronald B. Chase

U.S. Army Corps of Engineers - Detroit District

Academic Consultant for the Lake Michigan Potential Damages Study (Ronald B. Chase and William W. Montgomery) - January 22-24, 1997, October 14-16, 1998, April ___, 1999.

U.S. Army Research Office Progress Reports (Alan E. Kehew)

July 19, 1996
July 22, 1997

Presentations at Professional Meetings

Annual Meetings of the Geological Society of America - 1996 (2), 1997 (2), 1998 (2), 1999 (1).

Meeting of the International Association of Great Lakes Research - 1999.

University Presentations (Ronald B. Chase)

Grand Valley State University
Michigan State University
Western Michigan University (2)

Working Relationships

August 26 - October 12, 1996 - Geotechnical testing and soil classification of glacial materials susceptible to mass movements. Tests conducted by William W. Montgomery at the U.S. Army Corps of Engineers - Waterways Experiment Station.

February 3 - 20, 1997 - Use of the U.S. Army Corps of Engineers - Detroit District Geographic Information system (GIS) for historic slope recession studies by William W. Montgomery.

May 30-31, 1997 - Group discussion of stability relationships associated with variable stratigraphy and hydraulic conditions in the study area on the Western Michigan University campus arranged by Ronald B. Chase. Participants were from the U.S. Army Corps of Engineers - Detroit District and Chicago Regional Offices, the State of Michigan Department of Environmental Quality, the U.S. Army Research Office, and private industry.

June 26, 1998 - Field trip leaders for an inspection of the Lake Michigan shoreline bluffs. Participants were members of the International Joint Commission for Waterways Regulation and members of the U.S. Army Corps of Engineers. (Ronald B. Chase and Alan E. Kehew).

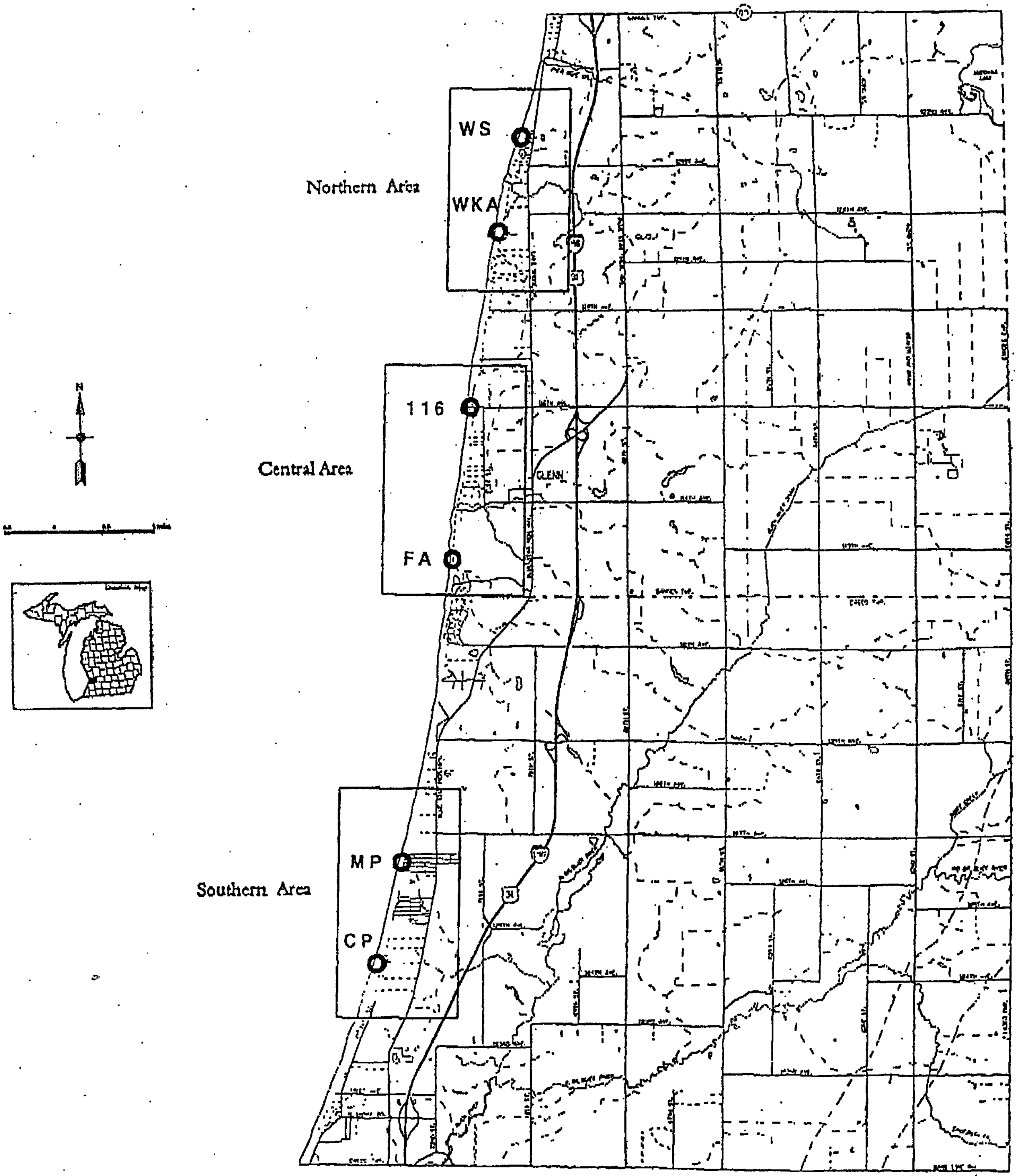


Figure 1: Location of the study area and the six monitoring sites displaying differing hydrostratigraphic conditions.

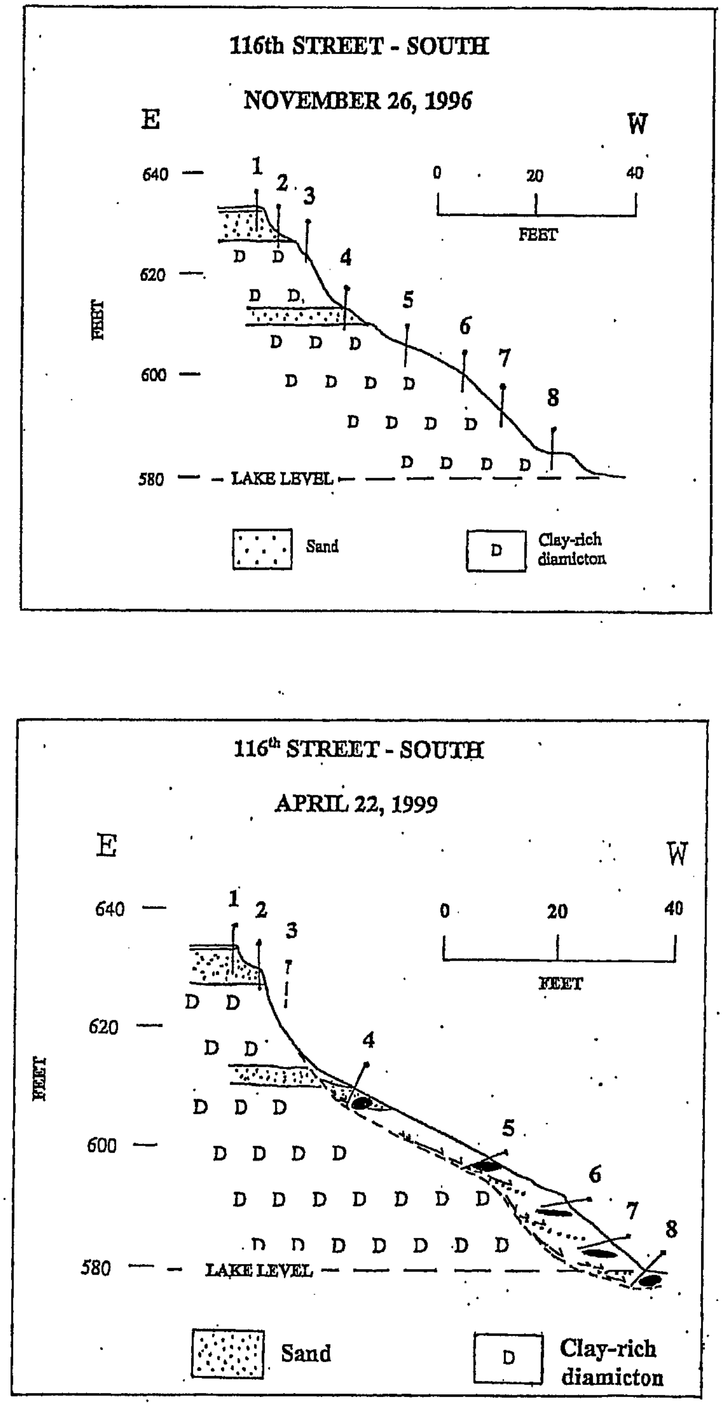
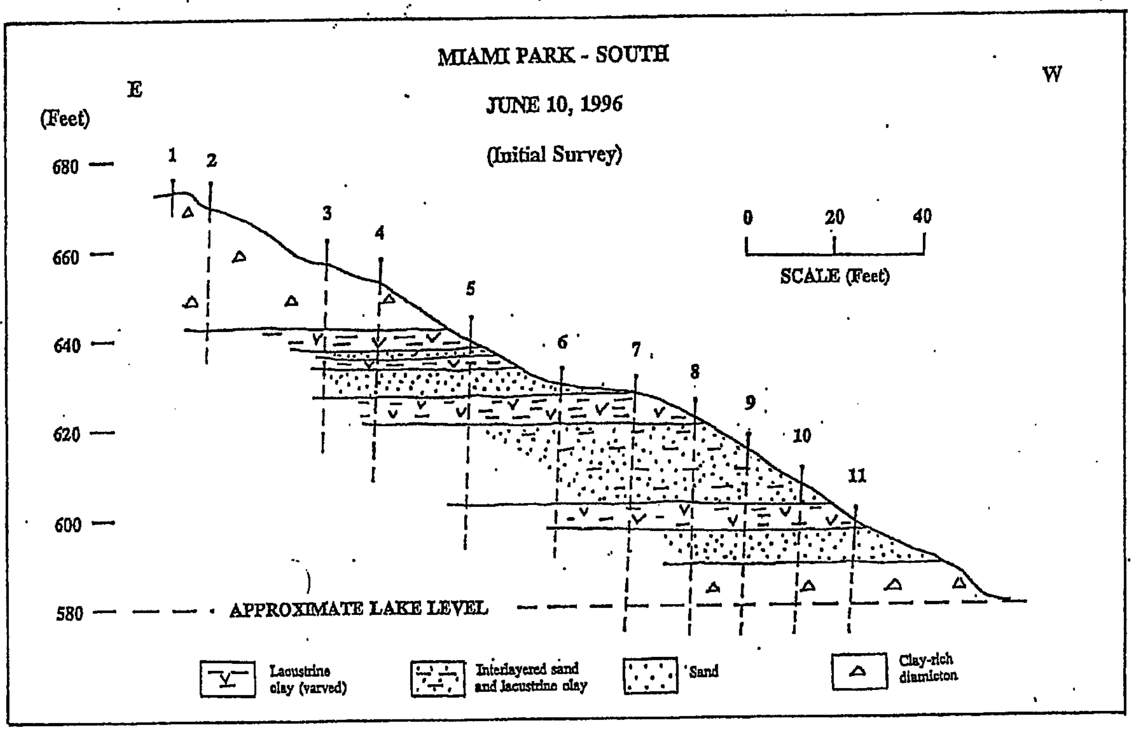


Figure 2: Slope containing mostly diamicton (till), some sand layers, and minimal perched ground water. A) Displacement survey system at the outset of monitoring. B) Displacement survey system after 2 ½ years of monitoring. Note the shallow, simple shear displacement of slumped material.



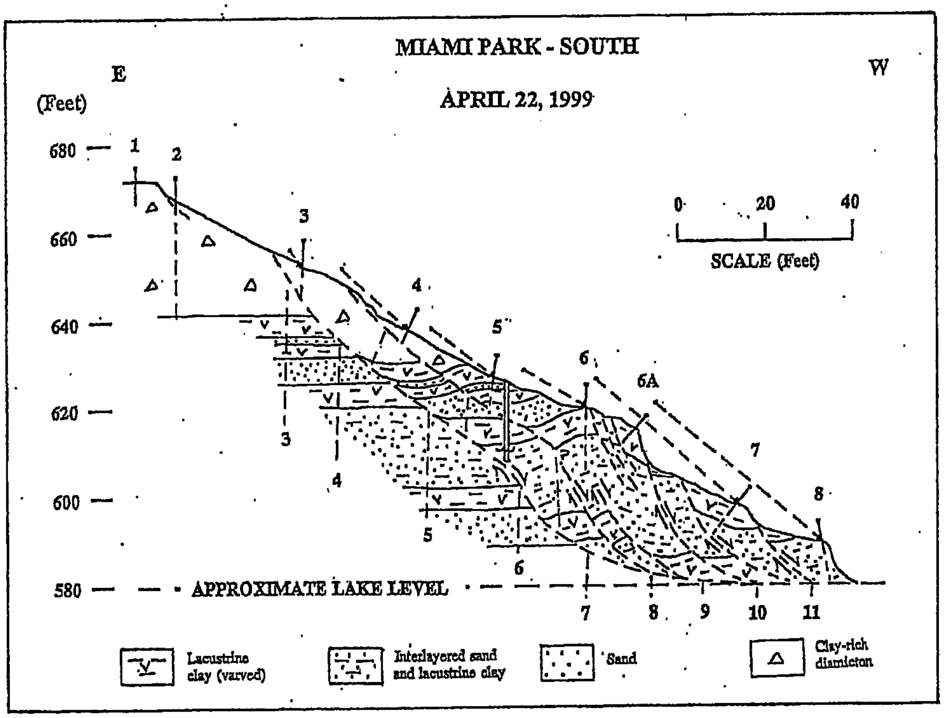


Figure 3: Slope containing interlayered diamicton (till), sand, and lacustrine silt/clay with significant perched ground water. A) Displacement survey system at the outset of monitoring. B) displacement survey system after three years of monitoring. Note the deeper-seated shear movements and general forward collapse of the ground surface above curved shear planes. Dashed lines at the base of survey poles are displacement vectors.

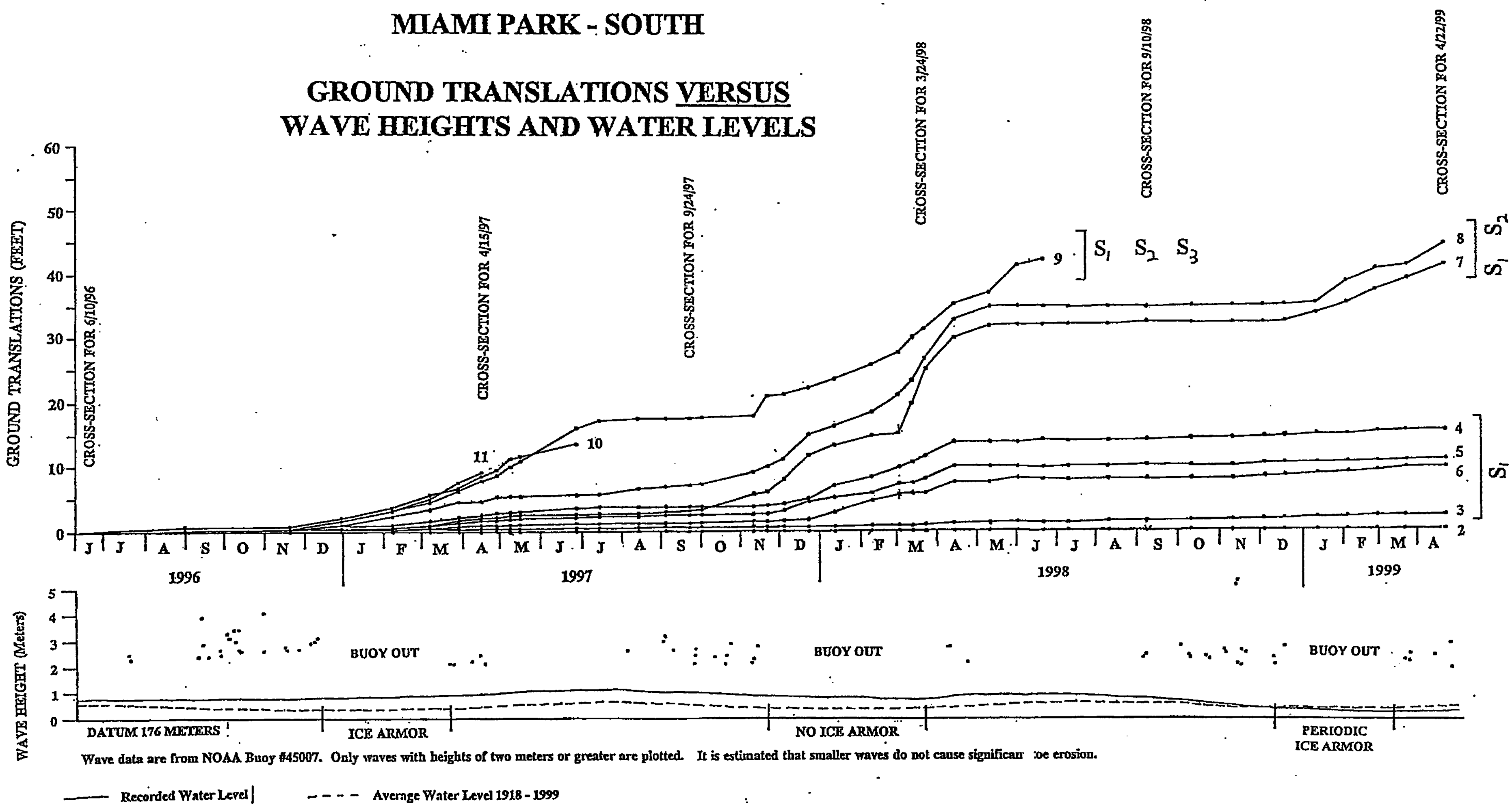


Figure 4: Relationship between displacements at the Figure 3 site and wave activity that reached the toe of the bluff. Note how accelerated movements in the late fall are proceeded by storm events.

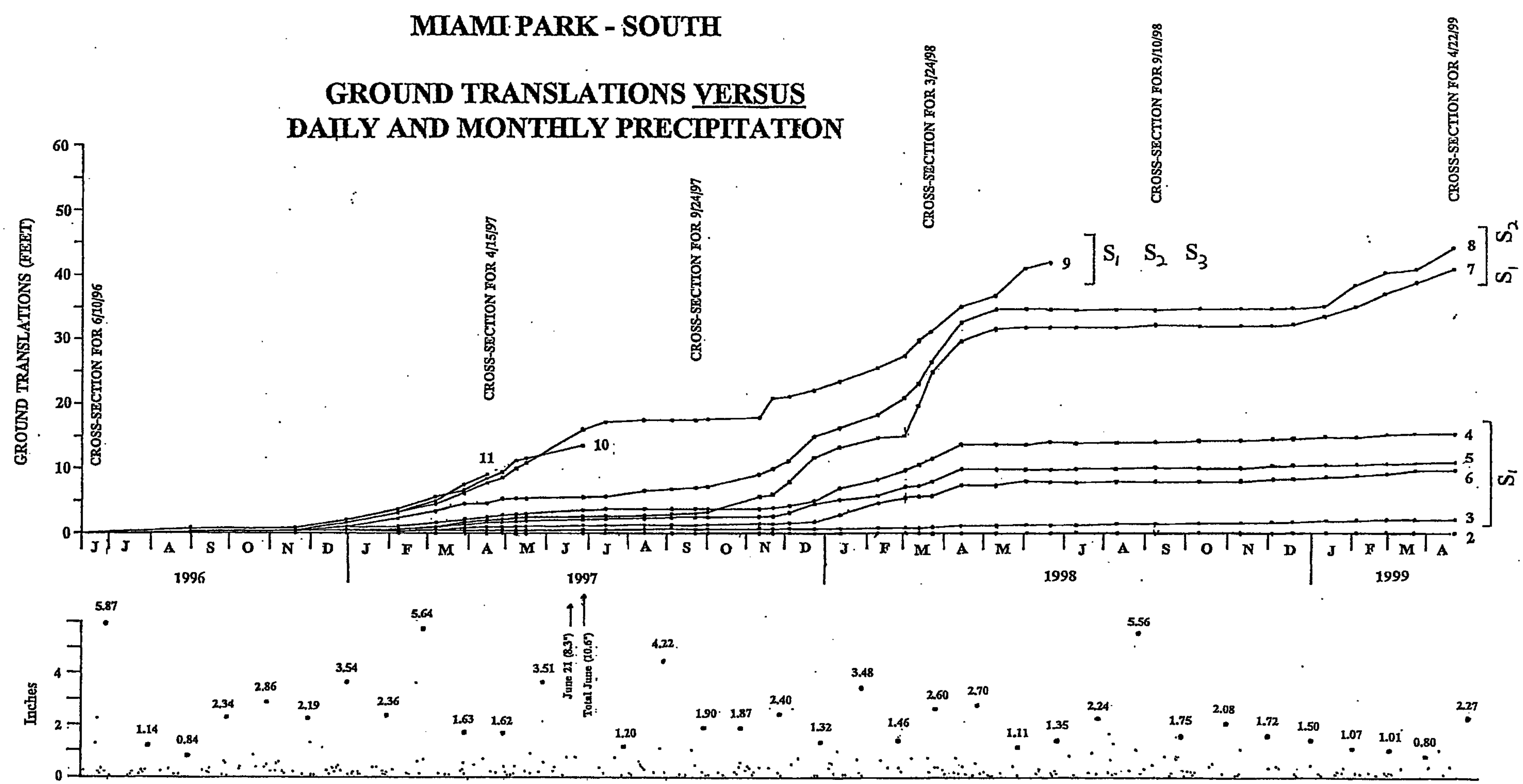


Figure 5: Relationships between displacements at the Figure 3 site and precipitation. Precipitation levels were relatively steady during bluff displacement with the exceptions of one major rain event (June 21-22, 1997) and the general reduction of precipitation (accompanied by falling lake levels) in late 1998 - early 1999.

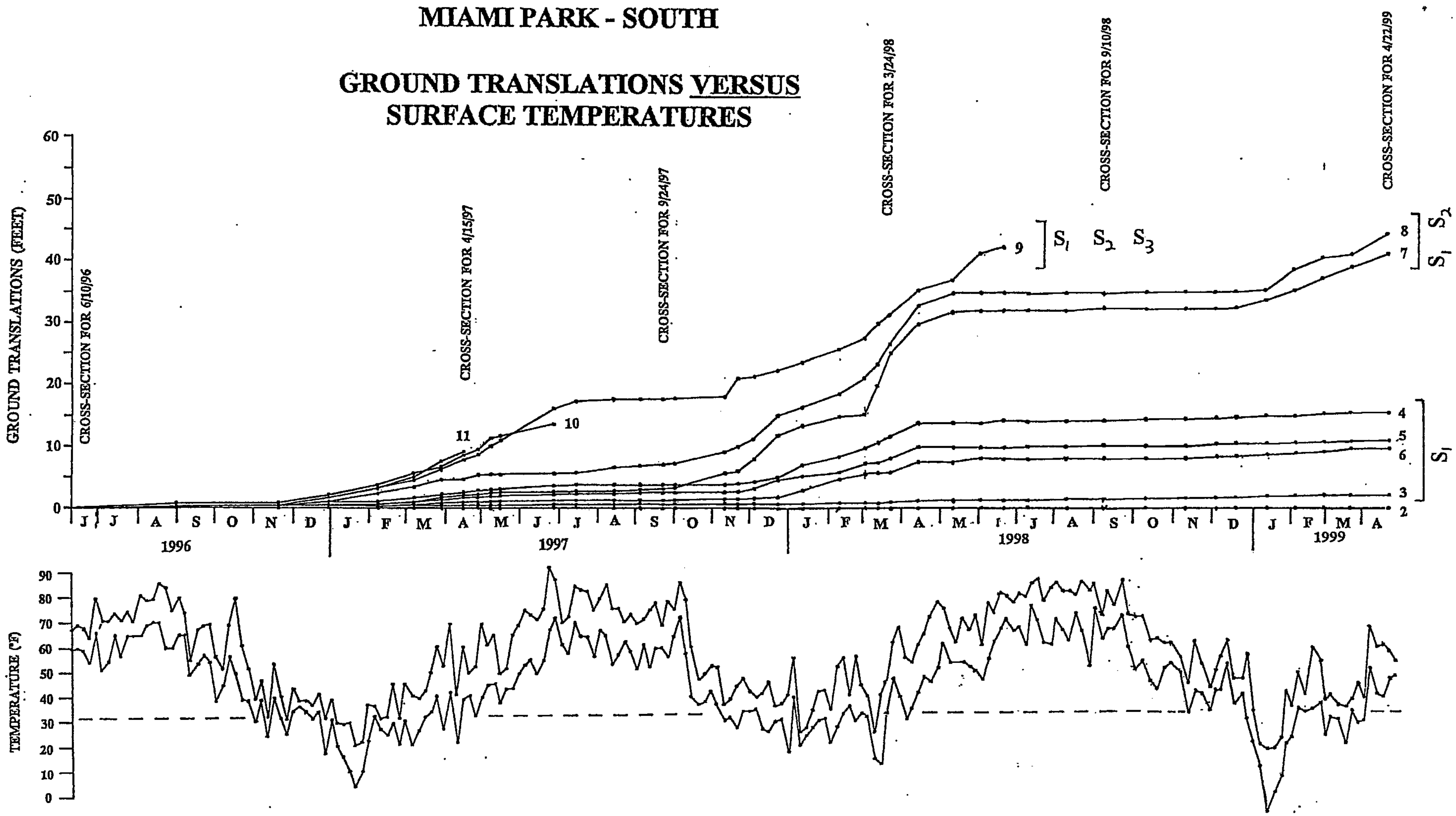


Figure 6: Relationships between displacements at the Figure 3 site and atmospheric temperatures. Note how accelerated bluff movements correspond with periods of freezing at the bluff surface.

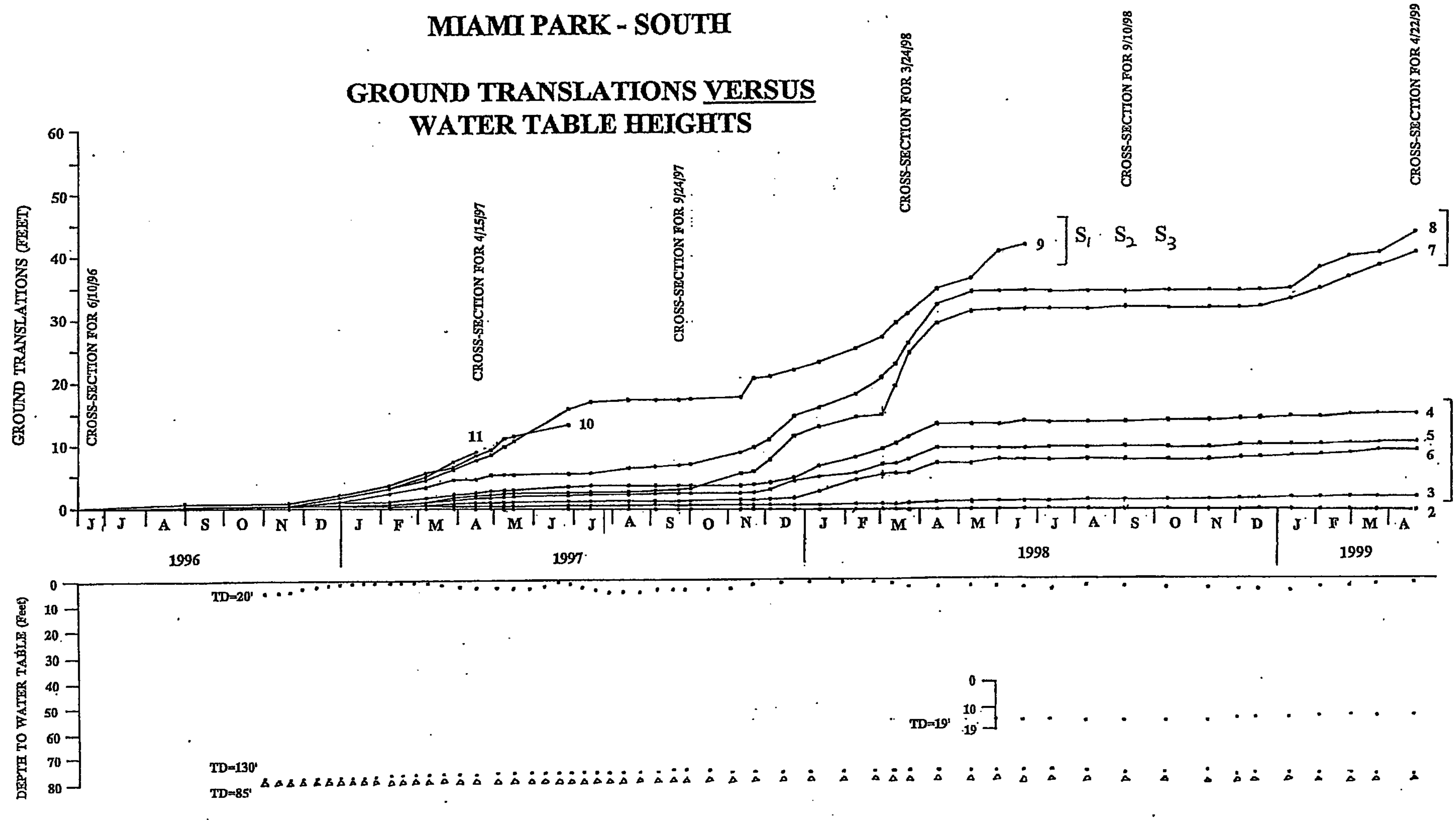


Figure 7: Relationships between displacements at the figure 3 site and perched ground water levels. Note how the standing water level in the shallow (perched water - recording) piezometer rises and falls during the periods of bluff surface freezing.